

TRANSGENIC FISH AND BETA-CATENIN SIGNALING PATHWAY MODEL

CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application
5 No. 60/416,504, filed October 3, 2002. This application is incorporated herein by
reference.

BACKGROUND OF THE INVENTION

The present invention is directed to a Lef1/β-catenin-dependent reporter and to
transgenic fish containing this reporter. The present invention is also directed to the use
10 of the reporter and the transgenic fish as a model for the β-catenin signaling pathway.
The model is useful for identifying genes in the β-catenin signaling pathway and for
identifying drugs that can modulate the β-catenin signaling pathway. Such drugs are
useful for treating or preventing melanoma, colorectal cancer, and osteoporosis, among
other disease conditions.

15 The publications and other materials used herein to illuminate the background of
the invention, and in particular, cases to provide additional details respecting the practice,
are incorporated by reference, and for convenience are referenced in the following text by
author and date and are listed alphabetically by author in the appended bibliography.

20 Secreted Wnt ligands activate receptor-mediated signal transduction pathways,
resulting in changes in gene expression, cell behavior, cell adhesion, and cell polarity.
Investigations of these pathways have been driven for two decades by the knowledge that
Wnt signaling is involved in both embryonic development and cancer. This knowledge
has fostered a rigorous scientific dissection of Wnt signaling on the basis of genetic
studies in the mouse *Mus musculus*, the fruit fly *Drosophila melanogaster*, the nematode
25 *Caenorhabditis elegans*, and the zebrafish *Danio rerio*, as well as cell biological and

biochemical studies in mammalian cultured cells and the frog *Xenopus laevis*. This worldwide effort has established that multiple Wnt signaling pathways are activated by a multigene family of Wnt ligands.

The first Wnt pathway to be discovered, and the best understood, is the canonical
5 Wnt pathway that activates the function of β -catenin shown in FIGURE 2, with more components, interactions, and target genes described in the canonical STKE Connections Map Wnt/ β -catenin Pathway (Moon, 2002a). Acting through a core set of proteins that are highly conserved in evolution, this pathway regulates the ability of β -catenin to activate transcription of specific target genes. This regulation, in turn, results in changes
10 in expression of genes that modulate cell fate, proliferation, and apoptosis. Components of the β -catenin signaling pathway are also regulated by other signals (FIGURE 2), promoting interest in understanding how Wnts can function in combination with other signaling pathways. As more signaling pathways are added to the STKE Connections Maps, it will be possible for both casual users and experts to better understand and predict
15 the outcome of increasingly complex combinatorial signaling.

Activation of the Wnt/ β -catenin signaling pathway holds both promise and perils for human medicine. The perils have been known for some time -- activation of this signaling pathway through loss-of-function mutations in the tumor suppressors adenomatous polyposis coli (APC) protein and axin, or through gain-of-function
20 mutations in β -catenin itself, are linked to diverse human cancers, including colorectal cancers and melanomas (Polakis, 2000). This connection has fueled a search for Wnt/ β -catenin pathway antagonists, which may become lead compounds for anticancer drugs. Greater knowledge of the Wnt/ β -catenin pathway may benefit patients with other diseases and conditions, because this pathway is involved in regulating angiogenesis
25 (Ishikawa et al., 2001; Wright et al., 1999), adipogenesis (Ross et al., 2000), and stem cell proliferation (Taipale and Beachy, 2001). For example, in the area of bone density, loss of function of a Wnt/ β -catenin pathway co-receptor, low-density lipoprotein receptor-related protein 5 (LRP5), results in low bone mass in children and heterozygous parents
30 (Gong et al., 2001). Conversely, apparent gain-of-function mutations in the same gene result in an autosomal dominant high bone-mass trait (Little et al., 2002). Thus, both antagonists and agonists of components of the Wnt/ β -catenin pathway may prove therapeutic in cancer and in stimulating cell and bone replacement, respectively.

Given the clear link between the Wnt/β-catenin signaling pathway and human diseases, and the conservation of molecular functions across many animal taxa, understanding the mechanisms of Wnt signaling benefit substantially from studies in model systems. The specific pathways in the STKE Connections Maps help to promote 5 the uses of model organisms to understand Wnt/β-catenin signaling. Currently, pathways in *Drosophila* (Boutros and Perriman, 2002), *C. elegans* (Bowerman, 2002a; Bowerman, 2002b; Bowerman, 2002c; Bowerman, 2002d) and *Xenopus* (Moon 2002b) are available, with future additions to include pathways for mouse, chicken, and zebrafish. Supporting 10 this goal of including pathways from more species, much of the earliest work on Wnt signaling and its effects on adhesion and the cytoskeleton was conducted on mammalian cells in culture (Hinck et al., 1994), and subsequent work on the mouse has led to numerous discoveries, including the roles of Wnts as mitogens in the nervous system (Megason and McMahon, 2002), and as essential signaling factors in formation of the 15 limbs (Martin, 2001), kidneys (Kispert et al., 1998), and female reproductive system (Heikkila et al., 2001). For a further review of Wnt pathway studies, see Moon et al. (2002).

The best characterized cellular output of Wnt/β-catenin signaling is the transcriptional activation of downstream target genes. Following Wnt pathway activation, cytoplasmic β-catenin accumulates and enters the nucleus, where it interacts 20 with the Lef/Tcf class of transcription factors (Eastman and Grosschedl, 1999; Sharpe et al., 2001). In zebrafish, two members of this family of HMG box proteins, Lef1 and Tcf3 (Headless, Hdl), have been implicated in early development (Dorsky et al., 1999; Pelegri and Maischein, 1998; Kim et al., 2000). Lef1 has been shown to act as a β-catenin-dependent transcriptional activator through its interactions with other 25 coactivator molecules (Billin et al., 2000). Tcf3 is a transcriptional repressor in the absence of β-catenin (Brannon et al., 1999; Roose et al., 1998). Upon β-catenin binding, Tcf3-mediated repression is relieved by an unknown mechanism. Both proteins bind to similar upstream regulatory DNA sequences, termed Lef binding sites (Waterman et al., 1991).

30 Analysis of a *headless* mutation in zebrafish has suggested that the main role of this gene during development is to repress downstream targets in the forebrain (Kim et al., 2000), in part because mutant embryos can be rescued by expression of a form of

Tcf3 that does not bind β -catenin. Other potential Tcf3 targets in *Xenopus*, such as *siamois*, require Lef binding sites only for their repression, and not for activation (Brannon et al., 1997). The question has therefore arisen of whether Tcf3 proteins ever act as gene activators *in vivo* or only as repressors that can be inactivated by Wnt 5 signaling.

Although Wnts are expressed throughout the developing embryo, the range of Wnt signaling *in vivo* has been difficult to determine. As a result, the cell populations and target genes that respond to Wnt/ β -catenin signals during development and in disease conditions are unidentified. In order to understand the multiple roles played by 10 Wnt/ β -catenin signaling, it is important to identify these very cell populations and genes. The CNS has remained particularly unexplored with respect to Wnt targets, considering that it was the first region to be identified as expressing a vertebrate *wnt* gene (Wilkinson et al., 1987) and has been subsequently shown to express numerous other Wnts as well 15 (Hollyday et al., 1995). Overexpression and loss-of-function studies have suggested roles for Wnts throughout the CNS (Dickinson et al., 1995; Ikeya et al., 1997).

Thus, it is desired to develop model systems that can be used to (a) identify genes 20 that modulate the β -catenin signaling pathway, (b) studying the relationship between the β -catenin signaling pathway and disease conditions, such as melanoma, colorectal cancer and osteoporosis among others, and (c) screen compounds to identify drugs that can modulate the β -catenin signaling pathway.

SUMMARY OF THE INVENTION

The present invention provides new tools for determining the role the β -catenin 25 signaling pathway plays in the physiology and pathology of the various disease conditions including, but not limited to, melanoma, colorectal cancer and osteoporosis. The tools are a Lef1/ β -catenin-dependent reporter and transgenic fish, particularly 30 transgenic zebrafish, that have integrated into their genomes a transgene encoding the Lef1/ β -catenin-dependent reporter. The transgenic fish with the reporter are useful for identifying genes that modulate the β -catenin signaling pathway and for identifying cell populations with an active β -catenin signaling pathway. The transgenic fish are also useful for screening compounds to identify drugs that can modulate the β -catenin signaling pathway. These drugs will be useful for treating or preventing the described disease conditions.

Thus, in one aspect, the present invention provides a nucleic acid encoding a Lef1/β-catenin-dependent reporter. In one embodiment, the nucleic acid comprises 4 consensus Lef binding sites, a minimal promoter derived from the mouse cFos gene (Accession No. AF332140) and a reporter gene downstream of a TOPFLASH promoter 5 and upstream of a SV40 polyadenylation site. In one aspect of this embodiment, the reporter gene is wildtype GFP. In a second aspect of this embodiment, the reporter gene is the d2GFP. A nucleic acid containing the d2GFP as the reporter gene has the map shown in FIGURE 1 and the sequence shown in SEQ ID NO:1.

In a second aspect, the present invention provides transgenic fish, particularly 10 transgenic zebrafish (*Danio rerio*), containing the nucleic acid encoding the Lef1/β-catenin-dependent reporter in its genome.

In a third aspect, the present invention provides a method for identifying genes that modulate the β-catenin signaling pathway. Such genes that are involved in specific 15 disease conditions are also identified according to this aspect of the invention.

In a fourth aspect, the present invention provides a method for screening 20 compounds to identify drugs useful for treating disease conditions involving the β-catenin signaling pathway, such as melanoma, colorectal cancer and osteoporosis.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and many of the attendant advantages of this invention will 25 become more readily appreciated as the same become better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings, wherein:

FIGURE 1 shows the map of the plasmid TOPdGFP. The nucleic acid sequence of this plasmid is set forth in SEQ ID NO:1. The nucleotide positions are defined from the first nucleotide in the sequence which is +1. The SV40 polyA is at nucleotides 20 38-243. The TOPFLASH enhancer is at nucleotides 3005-3374. The EGFP+pest is at nucleotides 3485-4327. The plasmid also includes an ampicillin resistance selectable marker.

FIGURE 2 shows core elements of the Wnt/β-catenin pathway, depicting how 25 activation of the Frizzled receptor by the Wnt ligand leads to activation of the function of β-catenin. This activation, in turn, activates gene expression leading to diverse cellular

responses in both embryonic development and in adults. Other pathways, such as integrin-linked kinase and p53, also regulate β -catenin.

FIGURES 3A-3I show that TOPdGFP expression reflects known domains of Wnt/ β -catenin signaling. Animal pole views are shown in FIGURE 3A and FIGURE 3B. 5 Lateral views are shown in FIGURES 2C-2F, with ventral to the left in FIGURE 3C and anterior to the left in FIGURES 3D-3F. FIGURE 3A: At dome stage (4 hpf), expression is localized to deep marginal cells on one side of the embryo, (arrowhead). FIGURE 3B: By shield stage, expression is observed in the ventrolateral marginal region and in the shield hypoblast (arrowhead). FIGURE 3C: At 80% epiboly, GFP expression expands 10 throughout the ventral mesoderm (vm). FIGURE 3D: Following gastrulation, mRNA is enriched at the posterior (right) end of the embryo. (Inset) Tailbud view shows exclusion of mRNA in the notochord (top). FIGURE 3E: At the six-somite stage, the first expression in the nervous system is seen at the presumptive midbrain/hindbrain boundary (mhb) and hindbrain, with an obvious gap between these regions. FIGURE 3F: By 15 18 somites, strong GFP expression is present in the midbrain region, with weaker expression in the ventral forebrain and tail mesoderm (tm). Lines indicate planes of section in FIGURES 2G-2I. FIGURE 3G: Longitudinal section at 18 somites, showing expression throughout the hindbrain and medial neural crest cells (arrowheads). FIGURE 3H: Transverse section through the hindbrain, with medial neural crest cells 20 marked by arrowheads. FIGURE 3I: Transverse section through the spinal cord, illustrating expression in the dorsomedial somite (som) closest to the neural tube, and in an intermediate zone of the CNS.

FIGURES 4A-4U show that reporter expression requires *lef1*, but not *hdl*, activity. Animal pole views are shown in FIGURE 4A and FIGURE 4B. Anterior views 25 with dorsal to the right are shown in FIGURES 4C, 4D, 4H, 4J, 4M, 4O, 4R, 4T. Posterior views with dorsal to the left are shown in FIGURES 4E, 4F, 4I, 4K, 4N, 4P, 4S, 4U). Arrowheads mark the rostral limit of the neurectoderm. At shield stage, *hdl* is expressed throughout the epiblast (FIGURE 4A), while *lef1* is expressed primarily in the germ ring (FIGURE 4B), similar to TOPdGFP (compare to FIGURE 3B). At bud stage, 30 *hdl* is expressed in the anterior neurectoderm and underlying prechordal plate (FIGURE 4C), while *lef1* expression is absent in this region (FIGURE 4D), similar to TOPdGFP (compare to FIGURE 4T). *hdl* is expressed very weakly in the tailbud (tb) at

5 bud stage (FIGURE 4E), while *lef1* is expressed at high levels in this region (FIGURE 4F), similar to TOPdGFP (compare to FIGURE 4U). Injection of a *hdl* morpholino phenocopies the *hdl* mutant at 36 hpf, causing loss of telencephalon and eyes (FIGURE 4G). The *hdl* morpholino results in rostral expansion of *pax2* (compare FIGURE 4H and FIGURE 4R), but has no effect on *tbx6* expression (compare FIGURE 4I and FIGURE 4S). Loss of *hdl* has no effect on expression of TOPdGFP in the anterior neurectoderm (compare FIGURE 4J and FIGURE 4T) or in the tailbud (compare FIGURE 4K and FIGURE 4U). Injection of a *lef1* morpholino results in loss of tail structures posterior to the yolk extension at 36 hpf (FIGURE 4L). While the *lef1* morpholino has no effect on *pax2* expression (compare FIGURE 4M and FIGURE 4R), it significantly decreases *tbx6* (compare FIGURE 4N and FIGURE 4S). Similarly, loss of *lef1* has no effect on anterior TOPdGFP expression (compare FIGURE 4O and FIGURE 4T), but it significantly decreases expression in the tailbud (compare FIGURE 4P and FIGURE 4U).

15 FIGURES 5A-5I show that TOPdGFP reporter expression is Wnt-responsive and dynamic throughout development. FIGURE 5A: Following injection with DNA encoding Wnt1-myc, ectopic reporter expression is induced outside the endogenous domain of GFP (arrowhead). (Inset) This cell expresses both Wnt1-myc, as detected by anti-myc immunostaining (red), and GFP (green). In all following panels, red 20 autofluorescence is shown for contrast. FIGURE 5B: Twelve-somite embryo. mbh, midbrain/hindbrain boundary. Box indicates region depicted at higher power in FIGURE 5C. FIGURE 5C: GFP is strongly expressed in the tail epiblast and hypoblast (arrowhead) and presomitic mesoderm (psm). FIGURE 5D: 24-hpf embryo. Box indicates region depicted at higher power in FIGURE 5E. FIGURE 5E: GFP is present at 25 low levels in the brain and higher levels in the otic vesicle (ov), migrating pigment cells (arrowhead), and posterior lateral line ganglion (pllg). FIGURE 5F: 48-hpf embryo. Left box indicates region depicted in FIGURE 5G and right box indicates region depicted in FIGURE 5H. FIGURE 5G: While expression decreases in the otic vesicle (ov), it is maintained at a high level in the posterior lateral line ganglion (pllg). FIGURE 5H: High- 30 power view of the posterior spinal cord shows specific TOPdGFP expression in individual neurons. FIGURE 5I: 72-hpf embryo. GFP is expressed in the dorsal midbrain, lens, and cranial ganglia (arrowheads).

FIGURES 6A-6I show that transverse cryosections of transgenic embryos show localized expression in regions of the CNS and other tissues. In all panels, red autofluorescence is shown for contrast. Spinal cord is outlined in white dotted lines in (FIGURES 6C, 6F, 6I). (FIGURES 6A-6C) 24 hpf; (FIGURES 6D-6F) 36 hpf; (FIGURES 6G-6I) 48 hpf. FIGURE 6A: Midbrain rostral to the eye is shown. FIGURE 6B: Section through caudal eye region. rpe, retinal pigmented epithelium. FIGURE 6C: Spinal cord section, showing individual GFP-labeled neurons. FIGURE 6D: Eye and midbrain region. Eyes are outlined in white dotted lines, lens is indicated by arrowhead. FIGURE 6E: Hindbrain section. Individual neurons in the ventral hindbrain express GFP. FIGURE 6F: In the spinal cord, expression is seen at multiple dorsal/ventral positions and in dorsal pigment cells (arrowheads). Pigment cells are identifiable by their morphology and position just below the ectoderm. FIGURE 6G: Extensive GFP expression is present in the dorsal midbrain. FIGURE 6H: Section just caudal to ear. pllg, posterior lateral line ganglion. FIGURE 6I: Spinal cord expression is similar to domains observed at 36 hpf.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

To examine the targets of Wnt/β-catenin signaling, an *in vivo* reporter system has been created that can identify β-catenin-responsive cells and genes. The TOPFLASH reporter has been extensively used to quantitate β-catenin-dependent transcription (Korinek et al., 1997), by expression of luciferase under the control of multiple Lef binding sites and a basal cFos promoter. In one embodiment, by employing a destabilized GFP, a transient reporter (TOPdGFP) has been created that is visible in living tissue with fluorescence optics. In a second embodiment, a wildtype GFP or any other suitable reporter molecule can be used in place of the destabilized GFP. Zebrafish is used as the transgenic organism, taking advantage of its optical clarity and rapid development to enable live imaging of reporter activity. A further advantage of zebrafish is its accessibility to both embryonic and genetic manipulations, vastly expanding the array of functional studies that can be undertaken with this system.

The transient reporter (TOPdGFP) as present in a plasmid vector is shown in FIGURE 1 and the nucleotide sequence is set forth in SEQ ID NO:1. Thus, one aspect of the present invention is an isolated nucleic acid that comprises a DNA molecule which functions as a reporter molecule. In a first embodiment, the DNA molecule comprises

nucleotides 3005-4336 of SEQ ID NO:1 contiguous to nucleotides 1-243 of SEQ ID NO:1. In a second embodiment, the DNA molecule comprises a nucleotide sequence having at least 80% identity, preferably at least 90% identity, more preferably, at least 95% identity and most preferably at least 98% identity, with this sequence and which has 5 the same reporter function. A second aspect of the present invention is this nucleic acid contained within a vector. One such vector is shown in FIGURE 1.

In a third embodiment, a wildtype GFP is used in place of the destabilized GFP. The vector shown in FIGURE 1 can be modified by substituting the wildtype GFP gene sequence, such as set forth in Genbank Accession No. M62653 for the nucleic acid 10 sequence of destabilized GFP. The destabilized GFP sequence includes nucleotides 3485-4330 of SEQ ID NO:1 which can be substituted by a coding sequence for wildtype GFP. A nucleic acid sequence encoding a wildtype GFP is shown in SEQ ID NO:2. In a fourth embodiment, the DNA molecule comprises a nucleotide sequence having at least 80% identity, preferably at least 90% identity, more preferably, at least 95% identity and 15 most preferably at least 98% identity, with this sequence and which has the same reporter function.

Many additional reporter proteins are known and have been used for similar purposes. These include enzymes, such as β -galactosidase, luciferase, and alkaline phosphatase, that can produce specific detectable products, and proteins that can be 20 directly detected. Virtually any protein can be directly detected by using, for example, specific antibodies to the protein. Any reporter which can be readily detected may be used in place of the destabilized or wildtype GFP.

A nucleic acid or fragment thereof has substantial identity with another if, when 25 optimally aligned (with appropriate nucleotide insertions or deletions) with the other nucleic acid (or its complementary strand), there is nucleotide sequence identity in at least about 60% of the nucleotide bases, usually at least about 70%, more usually at least about 80%, preferably at least about 90%, more preferably at least about 95% of the nucleotide bases, and more preferably at least about 98% of the nucleotide bases. A protein or fragment thereof has substantial identity with another if, optimally aligned, there is an 30 amino acid sequence identity of at least about 30% identity with an entire naturally- occurring protein or a portion thereof, usually at least about 70% identity, more usually at

least about 80% identity, preferably at least about 90% identity, more preferably at least about 95% identity, and most preferably at least about 98% identity.

Identity means the degree of sequence relatedness between two polypeptides or two polynucleotides sequences as determined by the identity of the match between two 5 strings of such sequences. Identity can be readily calculated. While there exist a number of methods to measure identity between two polynucleotide or polypeptide sequences, the term "identity" is well known to skilled artisans (*Computational Molecular Biology*, Lesk, A. M., ed., Oxford University Press, New York, 1988; *Biocomputing: Informatics and Genome Projects*, Smith, D. W., ed., Academic Press, New York, 1993; *Computer Analysis of Sequence Data*, Part I, Griffin, A. M., and Griffin, H. G., eds., Humana Press, New Jersey, 1994; *Sequence Analysis in Molecular Biology*, von Heinje, G., Academic Press, 1987; and *Sequence Analysis Primer*, Gribskov, M. and Devereux, J., eds., M Stockton Press, New York, 1991). Methods commonly employed to determine identity 10 between two sequences include, but are not limited to those disclosed in *Guide to Huge Computers*, Martin J. Bishop, ed., Academic Press, San Diego, 1994, and Carillo, H., and Lipman, D., *SIAM J Applied Math.* 48:1073 (1988). Preferred methods to determine identity are designed to give the largest match between the two sequences tested. Such 15 methods are codified in computer programs. Preferred computer program methods to determine identity between two sequences include, but are not limited to, GCG (Genetics Computer Group, Madison Wis.) program package (Devereux, J., et al., *Nucleic Acids Research* 12(1).387 (1984)), BLASTP, BLASTN, FASTA (Altschul et al. (1990); 20 Altschul et al. (1997)). The well-known Smith Waterman algorithm may also be used to determine identity.

As an illustration, by a polynucleotide having a nucleotide sequence having at 25 least, for example, 95% "identity" to a reference nucleotide sequence of is intended that the nucleotide sequence of the polynucleotide is identical to the reference sequence except that the polynucleotide sequence may include up to five point mutations per each 30 100 nucleotides of the reference nucleotide sequence. In other words, to obtain a polynucleotide having a nucleotide sequence at least 95% identical to a reference nucleotide sequence, up to 5% of the nucleotides in the reference sequence may be deleted or substituted with another nucleotide, or a number of nucleotides up to 5% of the total nucleotides in the reference sequence may be inserted into the reference sequence.

These mutations of the reference sequence may occur at the 5 or 3 terminal positions of the reference nucleotide sequence or anywhere between those terminal positions, interspersed either individually among nucleotides in the reference sequence or in one or more contiguous groups within the reference sequence.

5 Alternatively, substantial homology or (similarity) exists when a nucleic acid or fragment thereof will hybridize to another nucleic acid (or a complementary strand thereof) under selective hybridization conditions, to a strand, or to its complement. Selectivity of hybridization exists when hybridization which is substantially more selective than total lack of specificity occurs. Typically, selective hybridization will
10 occur when there is at least about 55% homology over a stretch of at least about 14 nucleotides, preferably at least about 65%, more preferably at least about 75%, and most preferably at least about 90%. The length of homology comparison, as described, may be over longer stretches, and in certain embodiments will often be over a stretch of at least about nine nucleotides, usually at least about 20 nucleotides, more usually at least
15 about 24 nucleotides, typically at least about 28 nucleotides, more typically at least about 32 nucleotides, and preferably at least about 36 or more nucleotides.

20 Nucleic acid hybridization will be affected by such conditions as salt concentration, temperature, or organic solvents, in addition to the base composition, length of the complementary strands, and the number of nucleotide base mismatches
25 between the hybridizing nucleic acids, as will be readily appreciated by those skilled in the art. Stringent temperature conditions will generally include temperatures in excess of 30EC, typically in excess of 37EC, and preferably in excess of 45EC. Stringent salt conditions will ordinarily be less than 1000 mM, typically less than 500 mM, and preferably less than 200 mM. However, the combination of parameters is much more important than the measure of any single parameter. The stringency conditions are dependent on the length of the nucleic acid and the base composition of the nucleic acid, and can be determined by techniques well known in the art. See, e.g., Asubel, 1992; Wetmur and Davidson, 1968.

30 Thus, as herein used, the term "stringent conditions" means hybridization will occur only if there is at least 95% and preferably at least 97% identity between the sequences. Such hybridization techniques are well known to those of skill in the art. Stringent hybridization conditions are as defined above or, alternatively, conditions under

overnight incubation at 42E C in a solution comprising: 50% formamide, 5x SSC (150 mM NaCl, 15 mM trisodium citrate), 50 mM sodium phosphate (pH7.6), 5x Denhardt's solution, 10% dextran sulfate, and 20 µg/ml denatured, sheared salmon sperm DNA, followed by washing the filters in 0.1x SSC at about 65E C.

5 The terms "isolated", "substantially pure", and "substantially homogeneous" are used interchangeably to describe a protein or polypeptide which has been separated from components which accompany it in its natural state. A monomeric protein is substantially pure when at least about 60 to 75% of a sample exhibits a single polypeptide sequence. A substantially pure protein will typically comprise about 60 to 90% w/w of a protein
10 sample, more usually about 95%, and preferably will be over about 99% pure. Protein purity or homogeneity may be indicated by a number of means well known in the art, such as polyacrylamide gel electrophoresis of a protein sample, followed by visualizing a single polypeptide band upon staining the gel. For certain purposes, higher resolution may be provided by using HPLC or other means well known in the art which are utilized
15 for purification.

Transgenic fish, particularly zebrafish, carrying the transient reporter, TOPdGFP, or other reporter molecules disclosed herein, including wildtype GFP, are produced in accordance with the present invention. The transgenic zebrafish are useful for identifying genes that modulate the β -catenin signaling pathway and for identifying drugs that
20 modulate the β -catenin signaling pathway.

The present invention relates to a method of determining the ability of a test agent or compound to modulate the β -catenin signaling pathway. A preferred method comprises administering the test agent to a transgenic fish which is expressing a Lef1/ β -catenin-dependent reporter and then assaying for changes in β -catenin signaling
25 pathway function. Such method is useful for identifying compounds which are able to ameliorate the symptoms that result from the involvement of the β -catenin signaling pathway and assessing the efficacy of the test compound on pathological symptoms that are associated with β -catenin signaling pathway.

Disclosed are transgenic fish, and a method of making transgenic fish, which
30 express a Lef1/ β -catenin-dependent reporter in stable and predictable tissue- or developmentally-specific patterns. Also disclosed are methods of using such transgenic fish. Such expression of the reporter allow the study of developmental processes, the

relationship of cell lineages, the assessment of the effect of specific genes and compounds on the development or maintenance of specific tissues or cell lineages, and the maintenance of lines of fish bearing mutant genes. The disclosed transgenic fish are characterized by homologous expression sequences in an exogenous construct introduced 5 into the fish or a progenitor of the fish.

As used herein, transgenic fish refers to fish, or progeny of a fish, into which an exogenous construct has been introduced. A fish into which a construct has been introduced includes fish which have developed from embryonic cells into which the construct has been introduced. As used herein, an exogenous construct is a nucleic acid 10 that is artificially introduced, or was originally artificially introduced, into an animal. The term artificial introduction is intended to exclude introduction of a construct through normal reproduction or genetic crosses. That is, the original introduction of a gene or trait into a line or strain of animal by cross breeding is intended to be excluded. However, fish produced by transfer, through normal breeding, of an exogenous construct 15 (that is, a construct that was originally artificially introduced) from a fish containing the construct are considered to contain an exogenous construct. Such fish are progeny of fish into which the exogenous construct has been introduced. As used herein, progeny of a fish are any fish which are descended from the fish by sexual reproduction or cloning, and from which genetic material has been inherited. In this context, cloning refers to 20 production of a genetically identical fish from DNA, a cell, or cells of the fish. The fish from which another fish is descended is referred to as a progenitor fish. As used herein, development of a fish from a cell or cells (embryonic cells, for example), or development of a cell or cells into a fish, refers to the developmental process by which fertilized egg cells or embryonic cells (and their progeny) grow, divide, and differentiate to form an 25 adult fish.

The examples illustrate the manner in which transgenic fish exhibiting the Lef1/β-catenin-dependent reporter can be made and used. The transgenic fish described in the examples, and the transgene constructs used, are particularly useful for detection of fish expressing the transgene, the identification of genes that modulate the β-catenin 30 signaling pathway and the identification of drugs that modulate the β-catenin signaling pathway.

Transgene constructs are the genetic material that is introduced into fish to produce a transgenic fish. Such constructs are artificially introduced into fish. The manner of introduction, and, often, the structure of a transgene construct, render such a transgene construct an exogenous construct. Although a transgene construct can be made 5 up of any nucleic acid sequences, for use in the disclosed transgenic fish it is preferred that the transgene constructs combine expression sequences operably linked to a sequence encoding an expression product. The transgenic construct will also preferably include other components that aid expression, stability or integration of the construct into the genome of a fish. As used herein, components of a transgene construct referred to as 10 being operably linked or operatively linked refer to components being so connected as to allow them to function together for their intended purpose. For example, a promoter and a coding region are operably linked if the promoter can function to result in transcription of the coding region.

Expression sequences are used in the disclosed transgene constructs to mediate 15 expression of an expression product encoded by the construct. As used herein, expression sequences include promoters, upstream elements, enhancers, and response elements. It is preferred that the expression sequences used in the disclosed constructs be homologous expression sequences. As used herein, in reference to components of transgene constructs used in the disclosed transgenic fish, homologous indicates that the 20 component is native to or derived from the species or type of fish involved. Conversely, heterologous indicates that the component is neither native to nor derived from the species or type of fish involved.

As used herein, expression sequences are divided into two main classes, 25 promoters and enhancers. A promoter is generally a sequence or sequences of DNA that function when in a relatively fixed location in regard to the transcription start site. A promoter contains core elements required for basic interaction of RNA polymerase and transcription factors, and may contain upstream elements and response elements. Enhancer generally refers to a sequence of DNA that functions at no fixed distance from the transcription start site and can be in either orientation. Enhancers function to increase 30 transcription from nearby promoters. Enhancers also often contain response elements that mediate the regulation of transcription. Promoters can also contain response elements that mediate the regulation of transcription.

Enhancers often determine the regulation of expression of a gene. This effect has been seen in so-called enhancer trap constructs where introduction of a construct containing a reporter gene operably linked to a promoter is expressed only when the construct inserts into the domain of an enhancer (O'Kane and Gehring, 1987; Allen et al., 5 1988; Kothary et al., 1988; Gossler et al., 1989). In such cases, the expression of the construct is regulated according to the pattern of the newly associated enhancer. Transgenic constructs having only a minimal promoter can be used in the disclosed transgenic fish to identify enhancers.

For expression of encoded peptides or proteins, a transgene construct also needs 10 sequences that, when transcribed into RNA, mediate translation of the encoded expression products. Such sequences are generally found in the 5' untranslated region of transcribed RNA. This region corresponds to the region on the construct between the transcription initiation site and the translation initiation site (that is, the initiation codon). The 5' untranslated region of a construct can be derived from the 5' untranslated region 15 normally associated with the promoter used in the construct, the 5' untranslated region normally associated with the sequence encoding the expression product, the 5' untranslated region of a gene unrelated to the promoter or sequence encoding the expression product, or a hybrid of these 5' untranslated regions. Preferably, the 5' untranslated region is homologous to the fish into which the construct is to be 20 introduced. Preferred 5' untranslated regions are those normally associated with the promoter used.

Transgene constructs for use in the disclosed transgenic fish encode a reporter 25 protein (for detection and quantitation of expression). As used herein, a reporter protein is any protein that can be specifically detected when expressed. Reporter proteins are useful for detecting or quantitating expression from expression sequences. For example, operatively linking nucleotide sequence encoding a reporter protein to a tissue specific expression sequences allows one to carefully study lineage development. In such studies, the reporter protein serves as a marker for monitoring developmental processes, such as cell migration. Many reporter proteins are known and have been used for similar 30 purposes in other organisms. These include enzymes, such as β -galactosidase, luciferase, and alkaline phosphatase, that can produce specific detectable products, and proteins that can be directly detected. Virtually any protein can be directly detected by using, for

example, specific antibodies to the protein. In accordance with the preferred embodiment of the present invention, the reporter protein is a destabilized green fluorescent protein (GFP).

5 The use of reporter proteins that, like GFP, are directly detectable without requiring the addition of exogenous factors are preferred for detecting or assessing gene expression during zebrafish embryonic development. A transgenic zebrafish embryo, carrying a construct encoding a reporter protein and a tissue-specific expression sequences, can provide a rapid real time *in vivo* system for analyzing spatial and temporal expression patterns of developmentally regulated genes.

10 The disclosed transgene constructs preferably include other sequences which improve expression from, or stability of, the construct. For example, including a polyadenylation signal on the constructs encoding a protein ensures that transcripts from the transgene will be processed and transported as mRNA. The identification and use of polyadenylation signals in expression constructs is well established. It is preferred that 15 homologous polyadenylation signals be used in the transgene constructs.

20 The disclosed constructs are preferably integrated into the genome of the fish. However, the disclosed transgene construct can also be constructed as an artificial chromosome. Such artificial chromosomes containing more than 200 kb have been used in several organisms. Artificial chromosomes can be used to introduce very large 25 transgene constructs into fish. This technology is useful since it can allow faithful recapitulation of the expression pattern of genes that have regulatory elements that lie many kilobases from coding sequences.

25 The disclosed constructs and methods can be used with any type of fish. As used herein, fish refers to any member of the classes collectively referred to as pisces. It is preferred that fish belonging to species and varieties of fish of commercial or scientific interest be used. Such fish include salmon, trout, tuna, halibut, catfish, zebrafish, medaka, carp, tilapia, goldfish, and loach.

30 The most preferred fish for use with the disclosed constructs and methods is zebrafish, *Danio rerio*. Zebrafish are an increasingly popular experimental animal since they have many of the advantages of popular invertebrate experimental organisms, and include the additional advantage that they are vertebrates. Another significant advantage of zebrafish is that, like *Caenorhabditis*, they are largely transparent (Kimmel, 1989).

The generation of thousands of zebrafish mutants (Driever et al., 1996); Haffter et al., 1996) provides abundant raw material for transgenic study of these animals. General zebrafish care and maintenance is described by Streisinger, 1984).

5 Zebrafish embryos are easily accessible and nearly transparent. Given these characteristics, a transgenic zebrafish embryo, carrying a construct encoding a reporter protein and tissue-specific expression sequences, can provide a rapid real time in vivo system for analyzing spatial and temporal expression patterns of developmentally regulated genes. In addition, embryonic development of the zebrafish is extremely rapid. In 24 hours an embryo develops rudiments of all the major organs, including a functional 10 heart and circulating blood cells (Kimmel, 1989). Other fish with some or all of the same desirable characteristics are also preferred.

15 The disclosed transgenic fish are produced by introducing a transgene construct into cells of a fish, preferably embryonic cells, and most preferably in a single cell embryo. Where the transgene construct is introduced into embryonic cells, the transgenic fish is obtained by allowing the embryonic cell or cells to develop into a fish. Introduction of constructs into embryonic cells of fish, and subsequent development of the fish, are simplified by the fact that embryos develop outside of the parent fish in most 20 fish species.

25 The disclosed transgene constructs can be introduced into embryonic fish cells using any suitable technique. Many techniques for such introduction of exogenous genetic material have been demonstrated in fish and other animals. These include microinjection (described by, for example, Culp et al., 1991), electroporation (described by, for example, Inoue et al., 1990; Muller et al., 1993; Murakami et al., 1994; Muller et al., 1992; Symonds et al., 1994), particle gun bombardment (Zelenin et al., 1991), and the use of liposomes (Szelei et al., 1994). Microinjection is preferred. The preferred method for introduction of transgene constructs into fish embryonic cells by 30 microinjection is described in the examples.

35 Embryos or embryonic cells can generally be obtained by collecting eggs immediately after they are laid. Depending on the type of fish, it is generally preferred that the eggs be fertilized prior to or at the time of collection. This is preferably accomplished by placing a male and female fish together in a tank that allows egg collection under conditions that stimulate mating. After collecting eggs, it is preferred

that the embryo be exposed for introduction of genetic material by removing the chorion. This can be done manually or, preferably, by using a protease such as pronase. A preferred technique for collecting zebrafish eggs and preparing them for microinjection is described in the examples. A fertilized egg cell prior to the first cell division is 5 considered a one cell embryo, and the fertilized egg cell is thus considered an embryonic cell.

After introduction of the transgene construct the embryo is allowed to develop into a fish. This generally need involve no more than incubating the embryos under the same conditions used for incubation of eggs. However, the embryonic cells can also be 10 incubated briefly in an isotonic buffer. If appropriate, expression of an introduced transgene construct can be observed during development of the embryo.

Fish harboring a transgene can be identified by any suitable means. For example, the genome of potential transgenic fish can be probed for the presence of construct sequences. To identify transgenic fish actually expressing the transgene, the presence of 15 an expression product can be assayed. Several techniques for such identification are known and used for transgenic animals and most can be applied to transgenic fish. Probing of potential or actual transgenic fish for nucleic acid sequences present in or characteristic of a transgene construct is preferably accomplished by Southern or Northern blotting. Also preferred is detection using polymerase chain reaction (PCR) or 20 other sequence-specific nucleic acid amplification techniques. Preferred techniques for identifying transgenic zebrafish are described in the examples.

Identifying the pattern of expression in the disclosed transgenic fish can be accomplished by measuring or identifying expression of the transgene in different tissues (tissue-specific expression), at different times during development (developmentally 25 regulated expression or developmental stage-specific expression), in different cell lineages (cell lineage-specific expression). These assessments can also be combined by, for example, measuring expression (and observing changes, if any) in a cell lineage during development. The nature of the expression product to be detected can have an effect on the suitability of some of these analyses. On one level, different tissues of a fish 30 can be dissected and expression can be assayed in the separate tissue samples. Such an assessment can be performed when using almost any expression product. This technique

is commonly used in transgenic animals and is useful for assessing tissue-specific expression.

This technique can also be used to assess expression during the course of development by assaying for the expression product at different developmental stages.

5 Where detection of the expression product requires fixing of the sample or other treatments that destroy or kill the developing embryo or fish, multiple embryos must be used. This is only practical where the expression pattern in different embryos is expected to be the same or similar. This will be the case when using the disclosed transgenic fish having stable and predictable expression.

10 A more preferred way of assessing the pattern of expression of a transgene during development is to use an expression product that can be detected in living embryos and animals. A preferred expression product for this purpose is the green fluorescent protein. A preferred form of GFP and a preferred technique for measuring the presence of GFP in living fish is described in the examples.

15 In zebrafish, the nervous system and other organ rudiments appear within 24 hours of fertilization. Since the nearly transparent zebrafish embryo develops outside its mother, the origin and migration of lineage progenitor cells can be monitored by following expression of an expression product in transgenic fish. In addition, the regulation of a specific gene can be studied in these fish.

20 Transgenic fish expressing the TOPdGFP reporter gene are useful for the identification of genes that modulate the β -catenin signaling pathway. Fish expressing the TOPdGFP reporter can be mated with fish raised from embryos that have been treated with a chemical mutagen (see for example: Imai et al., 2000; Hafter et al., 1996; Driever et al., 1996; Riley and Grunwald, 1995) or with an insertional retrovirus (see for example:

25 Golling et al., 2002; Burgess and Hopkins, 2000; Amsterdam and Hopkins, 1999). Alterations in the levels of the reporter gene product in progeny fish assessed, for example, by fluorescence measurements may represent the inactivation or over-expression of a gene(s) whose function has become altered by the presence of a chemically-derived or retrovirally-derived mutation.

30 It is also possible to detect genes that modulate the β -catenin signaling pathway by fertilizing eggs derived from fish expressing the TOPdGFP reporter gene with sperm derived from a library of fish bearing retroviral insertions. Alterations in the levels of the

reporter gene product in progeny may represent the inactivation or over-expression of a gene(s) whose function has become altered by the presence of a retroviral insertion. The nature of the retrovirus-altered gene can be determined by detection of the retroviral insertion which acts as a molecular tag of that gene.

5 The disclosed transgenic fish can be exposed to compounds to assess the effect of the compound on the modulation of the β -catenin signaling pathway. For example, test compounds can be administered to transgenic fish harboring an exogenous construct containing the expression sequence of a reporter protein. By comparing the expression of the reporter protein in fish exposed to a test compound to those that are not exposed, the
10 effect of the compound on the modulation of the β -catenin signaling pathway can be assessed. Test compounds can act as either inhibitors or activators of the reporter gene. In this manner, compounds which are useful as drugs for treating or preventing disease conditions associated with β -catenin signaling pathway, such as melanoma, colorectal cancer and osteoporosis, are identified.

15 The activity of β -catenin is regulated positively by signaling molecules of the Wnt family and negatively by molecules such as glycogen synthase kinase (GSK3 β) and adenomatous polyposis coli protein (APC). Compounds that modulate these actions may affect the activity of β -catenin and thus may have similar utility as drugs for treating or preventing disease conditions associated with β -catenin signaling pathway. Additionally,
20 β -catenin exerts a positive influence on *Microphthalmia*-associated transcription factor (MITF) which is known to modulate melanocyte differentiation and pigmentation (Widlund et al., 2002). The action of β -catenin on MITF is required as a potent mediator of growth for melanoma cells. Thus compounds that interfere with or alter the interaction between β -catenin and MITF may have utility in the treatment of melanoma.

25 A variety of test compounds can be evaluated in accordance with the present invention. In certain embodiments, the compounds to be tested can be derived from libraries (i.e., are members of a library of compounds). While the use of libraries of peptides is well established in the art, new techniques have been developed which have allowed the production of mixtures of other compounds, such as benzodiazepines (Bunin et al., 1992; DeWitt et al., 1993), peptoids (Zuckermann, 1994), oligocarbamates (Cho et al., 1993), and hydantoins (DeWitt et al., 1993). An approach for the synthesis of
30

molecular libraries of small organic molecules with a diversity of 10⁴-10⁵ as been described (Carell et al., 1994a; Carell et al., 1994b).

The compounds of the present invention can be obtained using any of the numerous approaches in combinatorial library methods known in the art, including:
5 biological libraries; spatially addressable parallel solid phase or solution phase libraries, synthetic library methods requiring deconvolution, the 'one-bead one-compound' library method, and synthetic library methods using affinity chromatography selection. The biological library approach is limited to peptide libraries, while the other four approaches are applicable to peptide, non-peptide oligomer or small molecule libraries of compounds
10 (Lam, 1997). Other exemplary methods for the synthesis of molecular libraries can be found in the art, for example in: Erb et al. (1994); Horwell et al (1996); Gallop et al. (1994).

15 Libraries of compounds may be presented in solution (e.g., Houghten, 1992), or on beads (Lam, 1991), chips (Fodor, 1993), bacteria (U.S. Pat. No. 5,223,409), spores (U.S. Pat. No. 5,223,409), plasmids (Cull et al., 1992) or on phage (Scott and Smith, 1990; Devlin, 1990; Cwirla et al., 1990; Felici, 1991). In still another embodiment, the combinatorial polypeptides are produced from a cDNA library.

20 Exemplary compounds which can be screened for activity include, but are not limited to, peptides, nucleic acids, carbohydrates, small organic molecules, and natural product extract libraries.

25 The goal of rational drug design is to produce structural analogs of biologically active polypeptides of interest or of small molecules with which they interact (e.g., agonists, antagonists, inhibitors) in order to fashion drugs which are, for example, more active or stable forms of the polypeptide, or which, e.g., enhance or interfere with the function of a polypeptide *in vivo*. Several approaches for use in rational drug design include analysis of three-dimensional structure, alanine scans, molecular modeling and use of anti-id antibodies. These techniques are well known to those skilled in the art. Such techniques may include providing atomic coordinates defining a three-dimensional structure of a protein complex formed by said first polypeptide and said second polypeptide, and designing or selecting compounds capable of interfering with the interaction between a first polypeptide and a second polypeptide based on said atomic coordinates.
30

Following identification of a substance which modulates or affects polypeptide activity, the substance may be further investigated. Furthermore, it may be manufactured and/or used in preparation, i.e., manufacture or formulation, or a composition such as a medicament, pharmaceutical composition or drug. These may be administered to 5 individuals.

A substance identified as a modulator of polypeptide function may be peptide or non-peptide in nature. Non-peptide "small molecules" are often preferred for many *in vivo* pharmaceutical uses. Accordingly, a mimetic or mimic of the substance (particularly if a peptide) may be designed for pharmaceutical use.

10 The designing of mimetics to a known pharmaceutically active compound is a known approach to the development of pharmaceuticals based on a "lead" compound. This approach might be desirable where the active compound is difficult or expensive to synthesize or where it is unsuitable for a particular method of administration, e.g., pure peptides are unsuitable active agents for oral compositions as they tend to be quickly 15 degraded by proteases in the alimentary canal. Mimetic design, synthesis and testing is generally used to avoid randomly screening large numbers of molecules for a target property.

Once the pharmacophore has been found, its structure is modeled according to its 20 physical properties, e.g., stereochemistry, bonding, size and/or charge, using data from a range of sources, e.g., spectroscopic techniques, x-ray diffraction data and NMR. Computational analysis, similarity mapping (which models the charge and/or volume of a pharmacophore, rather than the bonding between atoms) and other techniques can be used 25 in this modeling process.

A template molecule is then selected, onto which chemical groups that mimic the 25 pharmacophore can be grafted. The template molecule and the chemical groups grafted thereon can be conveniently selected so that the mimetic is easy to synthesize, is likely to be pharmacologically acceptable, and does not degrade *in vivo*, while retaining the biological activity of the lead compound. Alternatively, where the mimetic is peptide-based, further stability can be achieved by cyclizing the peptide, increasing its rigidity. 30 The mimetic or mimetics found by this approach can then be screened to see whether they have the target property, or to what extent it is exhibited. Further optimization or

modification can then be carried out to arrive at one or more final mimetics for *in vivo* or clinical testing.

The practice of the present invention employs, unless otherwise indicated, conventional techniques of chemistry, molecular biology, microbiology, recombinant 5 DNA, genetics, immunology, cell biology, cell culture and transgenic biology, which are within the skill of the art. See, e.g., Maniatis *et al.*, 1982; Sambrook *et al.*, 1989; Ausubel *et al.*, 1992; Glover, 1985; Anand, 1992; Guthrie and Fink, 1991; Harlow and Lane, 1988; Jakoby and Pastan, 1979; *Nucleic Acid Hybridization* (B. D. Hames & S. J. Higgins eds. 1984); *Transcription And Translation* (B. D. Hames & S. J. Higgins eds. 1984); 10 *Culture Of Animal Cells* (R. I. Freshney, Alan R. Liss, Inc., 1987); *Immobilized Cells And Enzymes* (IRL Press, 1986); B. Perbal, *A Practical Guide To Molecular Cloning* (1984); the treatise, *Methods In Enzymology* (Academic Press, Inc., N.Y.); *Gene Transfer Vectors For Mammalian Cells* (J. H. Miller and M. P. Calos eds., 1987, Cold Spring Harbor Laboratory); *Methods In Enzymology*, Vols. 154 and 155 (Wu *et al.* eds.), 15 *Immunochemical Methods In Cell And Molecular Biology* (Mayer and Walker, eds., Academic Press, London, 1987); *Handbook Of Experimental Immunology*, Volumes I-IV (D. M. Weir and C. C. Blackwell, eds., 1986); Riott, *Essential Immunology*, 6th Edition, Blackwell Scientific Publications, Oxford, 1988; Hogan *et al.*, *Manipulating the Mouse Embryo*, (Cold Spring Harbor Laboratory Press, Cold Spring Harbor, N.Y., 1986); 20 Westerfield, M., *The zebrafish book. A guide for the laboratory use of zebrafish (Danio rerio)*, (4th ed., Univ. of Oregon Press, Eugene, 2000).

EXAMPLES

The present invention is described by reference to the following Examples, which are offered by way of illustration and are not intended to limit the invention in any 25 manner. Standard techniques well known in the art or the techniques specifically described below were utilized.

EXAMPLE 1

MATERIALS AND METHODS

Generation of TOPdGFP: A 358-bp promoter/enhancer region of TOPFLASH 30 (Korinek *et al.*, 1997), containing 4 consensus Lef binding sites and a minimal promoter, was amplified by PCR. The 94-bp minimal promoter is derived from the mouse cFos gene (Accession No. AF332140), starting 38 bp 5' to the TATA box, and has no activity

in zebrafish on its own. This fragment was inserted into the vector pCS2+ (Turner and Weintraub, 1994), replacing the CMV promoter. The d2GFP gene (Clontech, Palo Alto, CA) was then inserted into this construct downstream of the TOP promoter and upstream of the SV40 polyadenylation site.

5 *DNA Injections and Production of Transgenic Fish:* Approximately 100 pg of TOPdGFP DNA was injected into a one-cell wild-type zebrafish embryo, into the yolk just below the blastoderm. Injections of 100–150 embryos were performed on multiple days. After 6 h, embryos were screened for GFP expression and positive embryos were sorted and raised to adulthood.

10 Adult fish were intercrossed and at least 100 embryos per pair were screened at 24 h postfertilization (hpf) by fluorescence microscopy for GFP expression. Because more male than female fish were generated, some males were screened by crossing to wild-type females. Out of 152 adult fish screened, one founder male that produced 10% transgenic progeny was identified. Heterozygous F₁ embryos were raised to adulthood to 15 establish a line and inter-crossed to generate homozygous progeny. This transgenic line has been given the allele designation TG(TOP:dGFP)w25. GFP imaging was performed by using a Nikon PCM2000 confocal microscope and images were processed with Adobe Photoshop 5.0.

20 For Wnt1 overexpression experiments, transgenic embryos were injected at the one-cell stage with 100 pg of pCS2 + wnt1-myc DNA. Injected embryos were fixed at 18 hpf, then processed for anti-myc immunostaining using a Cy3-labeled secondary antibody.

25 *In Situ Hybridizations:* *In situ* hybridization was performed as described previously (Oxtoby and Jowett, 1993). GFP probe was made by antisense transcription of TOPdGFP, using a T7 promoter present in the construct. Probe for *hdl* was made from a full-length clone isolated in our laboratory, subcloned into pCS2+. Probes for *pax2.1* (Krauss et al., 1991), *tbx6* (Hug et al., 1997), and *lef1* (Dorsky et al., 1999) were made as described previously. Images were taken with a Kodak DC290 digital camera and processed with Adobe Photoshop 5.0.

30 *Morpholino Injections:* Morpholino antisense oligonucleotides targeted to *lef1* and *hdl* were obtained from Gene Tools (Corvallis, OR). *lef1* MO sequence: 5'-

CTCCTCCACCTGACAACTGCGGCAT-3' (SEQ ID NO:3); *hdl* MO sequence: 5'-CTCCGTTAACTGAGGCATGTTGGC-3' (SEQ ID NO:4).

Approximately 1 ng of the morpholinos was injected into one-cell homozygous transgenic embryos that were fixed for *in situ* hybrid-ization at appropriate stages.

5 Injections of control morpholinos produced no effect on TOPdGFP expression.

Sections: Fixed embryos were rinsed in phosphate-buffered saline, equilibrated in 30% sucrose, embedded in Tissue-Tek OCT mounting medium, and frozen on dry ice. Sections (12 mM) were cut on a Reichert-Jung cryostat, rinsed, and coverslipped in Vectashield mounting medium.

10

EXAMPLE 2

GENERATION OF TOPDGFP TRANSGENIC ZEBRAFISH

The TOPdGFP reporter construct contains four consensus Lef binding sites and a minimal cFos promoter, driving a destabilized GFP transgene. This reporter should only be transcriptionally active in the presence of both stabilized β -catenin and Lef/Tcf proteins. When the TOPdGFP construct is injected into one-cell zebrafish embryos to test expression, GFP fluorescence is observed from approximately 6 hpf continuing throughout development. Expression was mosaic, and variations between individual embryos were apparent. Removal of the Lef binding sites resulted in no reporter expression in any injected embryo. We therefore concluded that the TOP-dGFP construct 15 was active in zebrafish and raised injected fish to adulthood.

20 After adult fish were screened by intercrossing or by outcrossing to a wild-type line, a mosaic founder fish that produced 10% transgenic embryos was recovered. In preliminary surveys, these embryos expressed GFP at high levels in the midbrain when observed under a fluorescence dissecting microscope. GFP fluorescence is not observed 25 before 12 hpf using confocal microscopy. This could be due to several factors, including low expression levels at early stages of development and positional effects of local genomic DNA. Confirming turnover of the destabilized GFP protein, many areas of expression visible at 12–16 hpf, such as presomitic mesoderm, were not visibly fluorescent 24 h later.

EXAMPLE 3
EARLY EXPRESSION OF TOPDGFP MIRRORS
KNOWN DOMAINS OF WNT/β-CATENIN SIGNALING

To examine whether TOPdGFP is expressed earlier in development than was evident by GFP fluorescence, *in situ* hybridization was performed on transgenic embryos at stages following the onset of zygotic transcription. Using this more sensitive technique, TOPdGFP expression is observed in known domains of Wnt signaling, consistent with its being a faithful reporter of this pathway. At 4 hpf, the first expression is observed in a small group of cells at the embryonic margin (FIGURE 3A). Although it is impossible to morphologically determine the future dorsal axis in zebrafish embryos at this stage, this expression is consistent with the site of nuclear β-catenin accumulation (Schneider et al., 1996) and the expression of β-catenin target genes such as *squint* and *bozozok* (Kelly et al., 2000; Ryu et al., 2001). During gastrulation, localized expression was observed in the embryonic shield (FIGURE 3B), supporting the assumption that the pregastrulation expression is dorsal. At shield stage, expression is observed in the ventrolateral mesoderm (FIGURE 3B), the site of the first known zygotic Wnt activity, produced by Wnt8 (Christian et al., 1991). This expression expands during gastrulation, covering most of the ventral mesoderm by 80% epiboly (vm; FIGURE 3C). By bud stage, all mesoderm in the posterior embryo expresses TOPdGFP, with the exception of the notochord (FIGURE 3D). The first observable expression in the neurectoderm was at 12 hpf, when GFP mRNA is detected in the midbrain–hindbrain boundary (mhb), hindbrain, and spinal cord (FIGURE 3E). Both neurectoderm and tail mesoderm expression continued until 18 hpf (FIGURE 3F), the latest stage we examined with this technique. In summary, at least four known domains requiring Wnt/β-catenin signaling are reported by TOPdGFP: the dorsal organizer (maternal β-catenin; Heasman et al., 1994; Schneider et al., 1996; Kelly et al., 2000), ventrolateral mesoderm (Wnt8; Lekven et al., 2001), tailbud (Wnt3a; Takada et al., 1994), and mhB (Wnt1; McMahon and Bradley, 1990).

In order to investigate early TOPdGFP expression in more detail, 18-hpf embryos were sectioned-stained by *in situ* hybridization. Through this analysis, transgene expression is observed in medial neural crest (FIGURES 3G and 3H), supporting earlier findings that Wnt signaling plays a role in neural crest fate specification (Dorsky et al., 1998; Dorsky et al., 2000). Sections through more caudal regions of the embryo showed

additional domains of expression including presumptive commissural interneuron progenitors (Bernhardt et al., 1990), and the medial lip of developing somites (FIGURE 3I).

EXAMPLE 4

5 LEF1, BUT NOT TCF3, REGULATES REPORTER EXPRESSION *IN VIVO*

Although the above observations provided circumstantial evidence that TOPdGFP reports endogenous Wnt signaling, it was possible that transgene expression in known Wnt-responsive domains was coincidental. However, it is apparent that TOPdGFP expression bears a resemblance to zygotic expression of *lef1* (compare FIGURE 3 to FIGURES 4B, 4D, and 4F). In contrast, TOPdGFP appears to be expressed in a complimentary pattern to *hdl* (Compare FIGURE 3 to FIGURES 4A, 4C, and 4E). Since *lef1* has been shown to mediate Wnt-dependent gene activation while *hdl* functions primarily as a repressor, the hypothesis that the activity of either gene is required for reporter expression was tested. To partially inhibit gene function, morpholino antisense oligonucleotides targeted against zebrafish *hdl* and *lef1* were injected. Both morpholinos can specifically block translation of the respective expression plasmids in reticulocyte lysates.

The function of *hdl* as a repressor of posterior neural gene expression led to test of whether the inhibition of *hdl* would expand TOPdGFP expression in transgenic embryos. 20 Injection of the *hdl* morpholino at the one-cell stage results in a phenotype indistinguishable from *hdl* mutant embryos at 36 hpf (FIGURE 4G). At bud stage, loss of *hdl* function results in the anterior expansion of midbrain markers such as *pax2* (FIGURE 4H), but has no effect on the expression of ventrolateral mesoderm markers such as *spt* (not shown) and *tbx6* (FIGURE 4I). Interestingly, the *hdl* morpholino does 25 not expand anterior TOPdGFP expression at shield stage (not shown) or bud stage (FIGURE 4J) and has no effect on posterior GFP expression (FIGURE 4K). One interpretation of this result is that there is no endogenous activation of Wnt/β-catenin target genes in anterior regions of the embryo, and that expression of more posterior genes such as *pax2* may be activated by other signals. Alternatively, it is possible that, in 30 the transgenic embryos, the TOPdGFP reporter is unable to respond to Tcf3 signaling due to limiting effects of the insertion into genomic DNA. It is not possible to distinguish

between these scenarios, but in either case it is clear that reporter expression is not repressed by *hdl* function in these fish.

The expression of *lef1* suggests that it may be a positive mediator of Wnt-dependent gene activation in the posterior ventrolateral mesoderm. Injection of the *lef1* morpholino results in tail truncations and loss of paraxial mesoderm, but normal head development (FIGURE 4L). The loss of *lef1* has no effect on *pax2* expression (FIGURE 4M), but it results in decreased expression of *spt* (not shown) and *tbx6* (FIGURE 4N). This experiment suggests that zebrafish *lef1* may play a role analogous to the redundant functions of *lef1* and *tcf1* in mouse posterior mesoderm development (Galceran et al., 1999). Supporting this hypothesis, no ortholog of *tcf1* has been isolated in zebrafish at this point. Following injection of the *lef1* morpholino, there is a striking decrease of TOPdGFP expression in the embryo at bud stage (FIGURES 4O and 4P), indicating that this gene is required for the expression of the reporter *in vivo*. Other work has suggested that ventrolateral mesodermal genes are targets of *wnt8* signaling during development (Lekven et al., 2001), and these results provide further evidence for this pathway.

These experiments illustrate an important aspect of TOPdGFP expression in the embryo. The transgene is able to report transcriptional activation mediated by *lef1*, but not repression mediated by *hdl*. Because the TOPdGFP construct contains no enhancer elements other than Lef binding sites, it is not surprising that it is inactive even in the absence of repression by *hdl*. Endogenous Wnt/β-catenin targets may be able to respond to other activating signals in the absence of *hdl*, due to additional elements controlling their expression. A limitation of the reporter is that it is not confirmed that it reflects all β-catenin-mediated transcription in the embryo. When regions of transgene expression are being examined, it is therefore important to keep in mind that GFP-expressing cells should be considered only as potential sites of β-catenin-activated transcription. However, because early TOPdGFP expression is dependent on Lef1 function, we believe that Lef1/β-catenin signaling is the most likely modulator of this transgene *in vivo*.

EXAMPLE 5

30 WNT1 IS SUFFICIENT TO ACTIVATE REPORTER EXPRESSION *IN VIVO*

Though it was demonstrated that TOPdGFP expression is dependent on *lef1* function, the question remained whether the reporter could respond to the entire Wnt

signaling pathway. To confirm that a Wnt signal was sufficient to elicit reporter expression, one-cell embryos were injected with a DNA construct encoding myc-tagged Wnt1 under the control of a CMV promoter. Examination of fixed injected embryos at 18 hpf, reveals the detection of coexpression of Wnt1-myc and GFP outside of the 5 endogenous TOPdGFP expression domain (FIGURE 5A). GFP expression is not detectable beyond the Wnt-misexpressing cell, which could be due to low levels of misexpression or low sensitivity of the reporter. In addition, not every cell that overexpressed Wnt1 was able to activate TOPdGFP. Again, this could be due to 10 limitations of our reporter, or to the lack of necessary signaling components such as Frizzled receptors at a given location in the embryo. A more rigorous test of the ability 15 of Wnts or other pathway components to activate TOPdGFP may require inducible activation of the pathway throughout the embryo. The current availability of heat-shock transgenic zebrafish (Halloran et al., 2000) will allow such experiments. In addition, it is reasonable to assume that other signaling pathways resulting in Lef1-dependent gene activation could activate the TOPdGFP reporter, such as activation of integrin-linked kinase (Novak et al., 1998). Despite these caveats, the result from this experiment indicates that 20 Wnt signals are capable of activating the TOPdGFP reporter.

EXAMPLE 6

DYNAMIC EXPRESSION OF TOPDGFP

20 IN THE CNS AND OTHER EMBRYONIC TISSUES

The TOPdGFP transgenic zebrafish was constructed to characterize novel 25 populations of potential β -catenin-responsive cells in the embryo. As a first step in this analysis, the reporter expression in late embryogenesis was examined focusing primarily on CNS expression -. At 12 hpf, GFP protein expression is observed throughout the CNS and tail mesoderm (FIGURES 5B and 5C). At this stage, a gap in expression exists at the 30 rostral hindbrain, similar to the gap observed in *wnt1* and *wnt3a* expression (Hollyday et al., 1995). In the tail, expression is highest in the presomitic mesoderm, with lingering expression in the newest somites. By 24 hpf, strong expression was observed in the dorsal midbrain, ventral forebrain, eye, ear, and spinal cord (FIGURE 5D). Closer examination of the hindbrain region revealed expression in peripheral sensory structures such as the otic epithelium, migrating neural crest, and cranial sensory ganglia (FIGURE 5E). These regions of expression persisted at 48 hpf (FIGURE 5F), with

specific expression in the posterior lateral line ganglion at this stage, when these cells are clearly postmitotic and have extended axons (FIGURE 5G). In the spinal cord, many individual neurons that express TOPdGFP appear to have undergone their final differentiation based on their position and morphology (FIGURE 5H). Finally, by 72 hpf, 5 the main areas of observable GFP expression were the dorsal midbrain, lens of the eye, and cranial sensory ganglia (FIGURE 5I). In summary, TOPdGFP expression undergoes dynamic changes during development from 12 to 72 hpf, disappearing from tail mesoderm and increasing throughout the CNS and sensory ganglia as these cells become postmitotic.

10 To examine the identity of GFP-expressing cells in more detail, fixed embryos were sectioned at multiple developmental stages. At 24 hpf, we observed uniform GFP expression throughout the neuroepithelium of the midbrain (FIGURE 6A). In the eye, expression was primarily limited to the retinal pigmented epithelium (RPE), ciliary margin, and lens (not shown), and was absent from the neural retina (FIGURE 6B). At 15 this stage, TOPdGFP is strongly expressed in individual spinal neurons (FIGURE 6C), a population that has not been previously identified as a Wnt target. By 48 hpf, continued strong expression in the dorsal midbrain and lens is observed, and decreased expression in the RPE and ciliary margin (FIGURE 6D). Scattered GFP expression is present at multiple dorsal/ventral positions in the hindbrain (FIGURE 6E) and spinal cord 20 (FIGURE 6F). In addition, dorsal pigment cells express high levels of the reporter at this stage (FIGURE 6F). Sections at 72 hpf confirmed our observations of expression in postmitotic midbrain neurons (FIGURE 6G), cranial sensory ganglia (FIGURE 6H), and spinal cord neurons (FIGURE 6I). Further anatomical and molecular characterization of these populations will be useful in examining possible roles of Wnt/β-catenin signaling in 25 their development.

It should be stressed that TOPdGFP is a reporter of β-catenin signaling, not Wnt activity *per se*. Potentially, any modulator of Lef1/β-catenin signaling could affect expression of the reporter. As previously mentioned, integrin-linked kinase signaling can activate β-catenin-responsive genes (Novak et al., 1998). In addition, the β-catenin 30 pathway can be negatively regulated by Wnt-independent mechanisms such as p53-mediated induction of Siah (Liu et al., 2001; Matsuzawa and Reed, 2001). Additional Lef/Tcf proteins such as Tcf4 are present in the embryo and their ability to activate the

transgene have not been explored. Furthermore, other molecules that can bind to Lef binding sites could regulate TOPdGFP completely independent of Lef1/β-catenin activity. As with any reporter system, unknown mechanisms could be responsible for expression patterns *in vivo*. While these possibilities cannot be completely ruled out, the above 5 examples show that at least the early expression of the transgene requires Lef1 activity.

It will be appreciated that the methods, fish and compositions of the instant invention can be incorporated in the form of a variety of embodiments, only a few of which are disclosed herein. It will be apparent to the artisan that other embodiments exist and do not depart from the spirit of the invention. Thus, the described embodiments are 10 illustrative and should not be construed as restrictive.

While the preferred embodiment of the invention has been illustrated and described, it will be appreciated that various changes can be made therein without departing from the spirit and scope of the invention.

BIBLIOGRAPHY

Allen et al. (1988). Transgene as probes for active chromosomal domains in mouse development. *Nature* 333:852-855.

Amsterdam, A. and Hopkins, N. (1999). Retrovirus-mediated insertional mutagenesis in zebrafish. *Methods in Cell Biology* 60:87-98.

Bernhardt, R.R. et al. (1990). Identification of spinal neurons in the embryonic and larval zebrafish. *J. Comp. Neurol.* 302:603-616.

Billin, A.N. et al. (2000). Beta-catenin-histone deacetylase interactions regulate the transition of LEF1 from a transcriptional repressor to an activator. *Mol. Cell. Biol.* 20, 10 6882-6890.

Boutros, M. and Perriman, N. (2002). *Drosophila* Wnt/Fz Pathway, *Science's STKE* (Connections Map, as seen in May 2002), http://stke.sciencemag.org/cgi/cm/CMP_6459.

Bowerman, B. (2002a). *C. elegans* T Cell Polarity Pathway, *Science's STKE* (Connections Map, as seen May 2002), http://stke.sciencemag.org/cgi/cm/CMP_10440 (2002a).

Bowerman, B. (2002b). *C. elegans* Gonadogenesis Pathway, *Science's STKE* (Connections Map, as seen May 2002), http://stke.sciencemag.org/cgi/cm/CMP_10698.

Bowerman, B. (2002c). *C. elegans* Endoderm Induction Pathway, *Science's STKE* (Connections Map, as seen May 2002), http://stke.sciencemag.org/cgi/cm/CMP_6104.

Bowerman, B. (2002d). *C. elegans* QL Neuroblast Migration Pathway, *Science's STKE* (Connections Map, as seen May 2002), http://stke.sciencemag.org/cgi/cm/CMP_9763.

Brannon, M. et al. (1999). XCtBP is a XTcf-3 co-repressor with roles throughout Xenopus development. *Development* 126, 3159-3170.

Brannon, M. et al. (1997). A beta-catenin/XTcf-3 complex binds to the siamois promoter to regulate dorsal axis specification in Xenopus. *Genes Dev.* 11, 2359-2370.

Bunin et al. (1992). *J. Am. Chem. Soc.* 114:10987.

Burgess, S. and Hopkins, N. (2000). Use of pseudotyped retroviruses in zebrafish as genetic tags. *Methods Enzymol* 327:145-161.

Carell et al. (1994a). *Angew. Chem Int. Ed. Engl.* 33:2059.

Carell et al. (1994b) *Angew. Chem. Int. Ed. Engl.* 33:2061.

Christian, J.L. et al. (1991). Xwnt-8, a *Xenopus* Wnt-1/int-1-related gene responsive to mesoderm-inducing growth factors, may play a role in ventral mesodermal patterning during embryogenesis. *Development* 111, 1045–1055.

5 Cho et al. (1993). *Science*. 261:1303.

Cull et al. (1992). *Proc Natl Acad Sci USA* 89:1865-1869.

Culp et al. (1991). High-frequency germ-line transmission of plasmid DNA sequences injected into fertilized zebrafish eggs. *Proc. Natl. Acad. Sci. USA* 88:7953-7957.

10 Cwirla et al. (1990). *Proc. Natl. Acad. Sci. USA* 87:6378-6382.

Devlin (1990). *Science* 249:404-406.

DeWitt et al. (1993). *Proc. Natl. Acad. Sci. USA* 90:6909.

Dickinson, M.E. et al. (1995). Dorsalization of the neural tube by the non-neural ectoderm. *Development* 121, 2099–2106.

15 Dorsky, R.I. et al. (1998). Control of neural crest cell fate by the Wnt signalling pathway. *Nature* 396, 370–373.

Dorsky, R.I. et al. (1999). Maternal and embryonic expression of zebrafish lef1. *Mech. Dev.* 86, 147–150.

Dorsky, R.I. et al. (2000). Direct regulation of nacre, a zebrafish MITF homolog required for pigment cell formation, by the Wnt pathway. *Genes Dev.* 14, 158–162.

20 Driever et al. (1996). A Genetic Screen for Mutations Affecting Embryogenesis in Zebrafish *Development* 123:37-46.

Eastman, Q. and Grosschedl, R. (1999). Regulation of LEF-1/TCF transcription factors by Wnt and other signals. *Curr. Opin. Cell Biol.* 11, 233–240.

25 Erb et al. (1994). *Proc. Natl. Acad. Sci. USA* 91:11422.

Felici (1991). *J Mol. Biol.* 222:301-310.

Fodor (1993). *Nature* 364:555-556.

Galceran, J. et al. (1999). Wnt3a2/2-like phenotype and limb deficiency in Lef1(2/2)Tcf1(2/2) mice. *Genes Dev.* 13, 709–717.

30 Gallop et al. (1994). *J. Med. Chem.* 37:1233.

Golling, G. et al. (2002). Insertional mutagenesis in zebrafish rapidly identifies genes essential for early vertebrate development. *Nat Genet* 31:135-140.

Gong, Y. et al. (2001). *Cell* 107:513.

Gossler et al. (1989). Mouse Embryonic Stem Cells and Reporter Constructs to Detect Developmentally Regulated Genes. *Science* 244:463-465.

Haffter et al. (1996). The identification of genes with unique and essential functions in the development of the zebrafish, *Danio rerio*. *Development* 123:1-36.

Halloran, M.C. et al. (2000). Laser-induced gene expression in specific cells of transgenic zebrafish. *Development* 127, 1953-1960.

Heasman, J. et al. (1994). Overexpression of cadherins and underexpression of beta-catenin inhibit dorsal mesoderm induction in early *Xenopus* embryos. *Cell* 79, 791-803.

Heikkila, M. et al. (2001). *J. Exp. Zool.* 290:616.

Hinck, L. et al. (1994). *J. Cell Biol.* 124:729.

Hollyday, M. et al. (1995). Wnt expression patterns in chick embryo nervous system. *Mech. Dev.* 52, 9-25.

Horwell et al (1996). *Immunopharmacology* 33:68.

Houghten (1992). *Biotechniques* 13:412-421.

Hug, B. et al. (1997). *tbx6*, a Brachyury-related gene expressed by ventral mesendodermal precursors in the zebrafish embryo. *Dev. Biol.* 183, 61-73.

Ikeya, M. et al. (1997). Wnt signalling required for expansion of neural crest and CNS progenitors. *Nature* 389, 966-970.

Imai, Y. et al. (2000). Analysis of chromosomal rearrangements induced by postmeiotic mutagenesis with ethylnitrosourea in zebrafish. *Genetics* 155:261-272.

Inoue et al. (1990). Electroporation as a new technique for producing transgenic fish. *Cell. Differ. Develop.* 29:123-128.

Ishikawa, T. et al. (2001). *Development* 128:25.

Kelly, C. et al. (2000). Maternally controlled (beta)-catenin-mediated signaling is required for organizer formation in the zebrafish. *Development* 127, 3899-3911.

Kim, C.H. et al. (2000). Repressor activity of Headless/Tcf3 is essential for vertebrate head formation. *Nature* 407, 913-916.

Kimmel (1989). Genetics and Early Development of Zebrafish. *Trends Genet* 5:283-288.

Korinek, V. et al. (1997). Constitutive transcriptional activation by a beta-catenin-Tcf complex in APC2/2 colon carcinoma. *Science* 275, 1784–1787.

Kothary et al. (1988). A transgene containing lacZ inserted into the dystonia locus is expressed in neural tube. *Nature* 335:435-437.

5 Krauss, S. et al. (1991). Expression of the zebrafish paired box gene pax[zf-b] during early neurogen-esis. *Development* 113, 1193–1206.

Lam, K.S. (1997). *Anticancer Drug Des.* 12:145.

Lam (1991). *Nature* 354:82-84.

Lekven, A.C. et al. (2001). Zebrafish *wnt8* encodes two Wnt8 proteins on a 10 bicistronic transcript and is required for mesoderm and neurectoderm patterning *Dev. Cell* 1, 103–114.

Little, R.D. et al. (2002). *Am. J. Hum. Genet.* 70:11.

Liu, J. et al. (2001). Siah-1 mediates a novel beta-catenin degradation pathway linking p53 to the adenomatous polyposis coli protein. *Mol. Cell* 7, 927–936.

15 Martin, G. (2001). *BioEssays* 23:865.

Matsuzawa, S.I. et al. (2001). Siah-1, SIP, and Ebi collaborate in a novel pathway for beta-catenin degradation linked to p53 responses. *Mol. Cell* 7, 915–926.

McMahon, A P. and Bradley, A. (1990). The Wnt-1 (int-1) proto-oncogene is required for development of a large region of the mouse brain. *Cell* 62, 1073–1085.

20 Megason, S.G and McMahon, A.P. (2002). *Development* 129:2087.

Moon, R. (020a). Wnt/β-catenin Pathway, *Science's STKE* (Connections Map, as seen in May 2002), http://stke.sciencemag.org/cgi/cm/CMP_5533.

Moon, R. (202b). *Xenopus* Egg Wnt/Beta-Catenin Pathway, *Science's STKE* (Connections Map, as seen May 2002), http://stke.sciencemag.org/cgi/cm/CMP_6031.

25 Moon, R. et al. (2002) The promise and perils of Wnt signaling through β-catenin. *Science* 296:1644-1646.

Muller et al. (1992). Introducing foreign genes into fish eggs with electroporated sperm as a carrier. *Mol. Mar. Biol. Biotechnol.* 1:276-281.

Muller et al. (1993). Efficient Transient Expression System Based on Square 30 Pulse Electroporation and In Vivo Luciferase Assay of Fertilized Fish Eggs. *FEBS Letters* 324:27-32..

Murakami, et al. (1994). Micromachined electroporation system for transgenic fish. *J. Biotechnol.* 34:35-42.

Novak, A. et al. (1998). Cell adhesion and the integrin-linked kinase regulate the LEF-1 and beta-catenin signaling pathways. *Proc. Natl. Acad. Sci. USA* 95, 4374–4379.

5 O'Kane, et al. (1987). Detection in situ of Genomic Regulatory Elements in *Drosophila*. *Proc. Natl. Acad. Sci. USA* 84:9123-9127.

Oxtoby, E. and Jowett, T. (1993). Cloning of the zebrafish krox-20 gene (krx-20) and its expression during hindbrain development. *Nucleic Acids Res.* 21, 1087–1095.

10 Pelegri, F. and Maischein, H. M. (1998). Function of zebrafish beta-catenin and TCF-3 in dorsoventral patterning. *Mech. Dev.* 77, 63–74.

Polakis, P. (2000). *Genes Dev.* 14:1837.

Riley, B.B. and Grunwald, D.J. (1995). Efficient induction of point mutations allowing recovery of specific locus mutations in zebrafish. *Proc Natl Acad Sci USA* 92:5997-6001.

15 Roose, J. et al. (1998). The Xenopus Wnt effector XTcf-3 interacts with Groucho-related transcriptional repressors. *Nature* 395, 608– 12.

Ross, S.E. et al. (2000). *Science* 289:950.

Ryu, S.L. et al. (2001). Regulation of dharma/bozozok by the Wnt pathway. *Dev. Biol.* 231, 397–409.

20 Schneider, S. et al. (1996). Beta-catenin translocation into nuclei demarcates the dorsalizing centers in frog and fish embryos. *Mech. Dev.* 57, 191–198.

Scott and Smith (1990). *Science* 249:386-390

Sharpe, C. et al. (2001). Wnt signalling: A theme with nuclear variations. *BioEssays* 23, 311–318.

25 Streisinger (1984). Attainment of Minimal Biological Variability and Measurements of Genotoxicity: Production of Homozygous Diploid Zebra Fish. *Natl. Cancer Inst. Monogr.* 65:53-58.

Symonds, et al. (1994). Electroporation of salmon sperm with plasmid DNA: evidence of enhanced sperm/DNA association. *Aquaculture* 119:313-327.

30 Szelei, et al. (1994). Liposome-mediated gene transfer in fish embryos. *Transgenic Res.* 3:116-119 (1994).

Taipale, J and Beachy, P.A. (2001). *Nature* 411:349.

Takada, S. et al.. (1994). Wnt-3a regulates somite and tailbud formation in the mouse embryo. *Genes Dev.* 8, 174–189.

Turner, D.L. and Weintraub, H. (1994). Expression of achaete-scute homolog 3 in Xenopus embryos converts ectodermal cells to a neural fate. *Genes Dev.* 8, 1434–1447.

5 Waterman, M.L. et al. (1991). A thymus-specific member of the HMG protein family regulates the human T cell receptor C alpha enhancer. *Genes Dev.* 5, 656–669.

Widlund H.R. et al. (2002). *Journal Cell Biol* 158:1079-1087.

Wilkinson, D.G. et al. (1987). Expression of the proto-oncogene int-1 is restricted to specific neural cells in the developing mouse embryo. *Cell* 50:79–88.

10 Wright, M. et al. (1999). *Biochem. Biophys. Res. Commun.* 263:384.

Zelenin, et al. (1991). The Delivery of Foreign Genes Into Fertilized Fish Eggs Using High-velocity Microprojectiles. *FEBS Letters* 287: 118-120.

Zuckermann. (1994). *J. Med. Chem.* 37:2678.

U.S. Patent No. 5,223,409

15